NASA/CR- 97- 208226

IN-91-CR

# Studies of Tenuous Planetary Atmospheres

A Final Report for Grant NAGW-3417: NASA Planetary Atmospheres Program

For the Period 8/1/96 to 7/31/97

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## SCIENTIFIC BACKGROUND

In order to understand the physical and chemical processes which produce the dust comae in comets and various tenuous planetary and planetary satellite (upper) atmospheres through interactions with their particle, field, and radiation environs, it is necessary analyze remotely observed and spacecraft data with physically meaningful models. With this in mind, we have undertaken a coupled program of theoretical modeling and complementary data analysis regarding the distribution of dust t in comets, and the global distributions of neutral and ionized gases in, and escape from, tenuous planetary atmospheres.

The nature of the atmospheres and ionospheres of Jupiter's natural satellites Io and Europa and their interactions with their surrounding radiation, and particles and fields environments is a very active and timely field of study. Various kinds of work, depending on different regime-dependent approaches have been adopted in recent years, with the hope of understanding the basic global structure of the atmospheres, and their interactions with solar radiation and with the Jovian plasma torus environment.

Io's interaction with Jupiter's corotating plasma torus has been studied for over 25 years. Io has a neutral atmosphere which is probably locally thick but rather uneven across its surface. (See Lellouch 1996 for an excellent review of pre-1996 literature.) The ultimate source for atmospheric gases appears to be the numerous active volcanoes on the surface, moderated by condensation and sublimation from the surface. The energetic particle environment near Io is responsible for the balance of the plasma heating, Joule heating, ionization, and surface and atmospheric sputtering, and in some form drives the escape of the neutral atmosphere (Schneider, Smyth, & McGrath, 1989).

The tenuous atmosphere portion of our work involves developing and applying coupled three-dimensional magnetohydrodynamic (MHD) and fully kinetic ion and neutral Direct Simulation Monte Carlo models to describe the upper atmospheres and ionosphere of Jupiter's planetary satellites and their interaction with the corotating plasma torus. This is first being done for Jupiter's moon Io and then for Europa.

The standard dust coma treatments originated with the pioneering work of Finson-Probstein (1968a&b) which considers the dust to consist of a population of spherical particles having a range of sizes with a distribution determined by a power law in particle diameter. The particles were considered to have a constant density, $\rho(a) = \rho_o$ independent of particle size. The light scattering properties, which are needed to describe the observed scattered radiation, and to calculate the radiation pressure acceleration on each particle size, were considered to be simply proportional to the geometric cross section of the particle implying that the light scattering efficiency, $Q_{sca}$, and the radiation pressure efficiency, $\eta_{rp}$, both equal unity and are independent of particle size. It is clear from the work of a number of investigators that these underlying assumptions are highly oversimplified for physical dark absorbing dust particles (e.g. see the review by Grün &Jessberger 1991).

The Finson-Probstein approach has been advanced in recent years to include various complex physical parameterizations including porous (fractal aggregate) size-dependent dust density, realistic radiation and radiation pressure scattering efficiencies for dark dielectrics, anisotropic production, and fragmentation (Fulle et al., 1993 & 1997; Konno et al., 1993; Combi 1994). The difficulty in interpreting observed monochromatic two-dimensional images of the coma and tail is that the parameter space is underconstrained. Even for complicated inversion techniques (Fulle et al.), it is necessary to adopt some of the parameterizations, fix some parameters, and solve for others. So, one can get a mathematical inversion that is only unique within the constraints of the underlying assumptions and parameterizations.

We (Combi 1994) had found that dust images of the coma provide evidence that the 1-to-1-to-1 Finson-Probstein type relationship between particle size, velocity, and radiation pressure, implicit in most dust coma analyses, does not hold in general. We arrived at a similar and independent suggestion as Fulle et al. (1993 & 1997) had: that particle fragmentation within and/or just outside the dusty-gas acceleration region ($r < 1000$km) would produce this effect. Analyses of the Giotto Halley Multicolor Camera images independently point to fragmentation (Konno et al. 1993; Keller et al. 1990).

The comet portion of our work involves combining a proven and developed comet dust model with elements from our gas coma model to study published data and complementary data through established collaborations with observers. This kind of collaboration between observer and modeler is an efficient and cost effective approach to maximizing scientific productivity.

## PROGRESS DURING THE PROJECT YEAR

This is technically a final report because it describes the progress at the end of the project year corresponding to the transfer of what is really a multi-year grant from administration by NASA Headquarters to Goddard Space Flight Center. The normal renewal proposal/progress report had been submitted in the typical timely fashion (February 1997) and the second year of funding adminstered by Goddard is already underway. This project has been hindered by a number events beyond our control both at NASA and in Michigan. Despite these, there has been significant progress toward our scientific goals. There was a long delay in the receipt of the funding of the first year award, and the authomatic no cost extension of the first year which we as Principal Investigators were told to request resulted effectively in an 8-month funding delay. We have also been slowed by the departure of Dr. Ronald Miller who left planetary and space research at the University of Michigan for an industrial research career. He was going to work on a number of tasks in this program. Before leaving he had developed the working core of a combined 2D axisymmetric kinetic atmosphere/ionosphere model for Io based on recent advances in Earh ionosphere modeling [Miller and Combi 1994; Miller et al. 1995] and our separate comet modeling program. A postdoctoral research associate, Dr. Rainer Bauske, joined our group during this project year in part to help with the work on Io modeling efforts. During this time he had begun reorganizing elements of the original model code into a more general and structured form with a number of goals in mind. With developments discussed below in the area of 3D MHD modeling and because of the complexity of dealing adequately with magnetized plasma flow, it became clear that it was prudent for Dr. Bauske to begin development of a 3D kinetic model rather than coming completely "up-to-speed" on the 2D code.

As a result of suggestions on the part of the peer and panel reviews of this proposal (and also consistent with the original aims), we began a program to make use of the advances of our colleagues at the University of Michigan in magneospheric modeling for studying the interaction of io with the plasma torus. A new numerical method has been developed for solving the full 3D MHD equations which resolves a number of diffuiculties that have plagued past attempts. The 3D version of the new method, multiscale adaptive upwind scheme for MHD (MHD-MAUS), has already been applied to the full comet solarwind interaction prolem as discussed in detail by Gombosi et al. [1996]. The model also now includes intrinsic magnetic fields, and so can be applied to planetary satellite interactions in the Jovian system.

The 3D MAUS-MHD model simulation is done on a Cartesian grid using octree adaptive mesh refinement (AMR). This makes optimal use of computer resources allowing problems with disparate scales and unusual and varying geometries to be modeled globally, while still retaining sufficient resolution locally to trap shocks and important features resulting from naturally occuring sharp gradients in the flow. The octree structure is a hierarchical cell structure, based on multigenerations of parent cells which can be split into 8 daughter cells. The approximate Rieman solver for ideal MHD is based on a second-order MUSCL-type scheme [van Leer 1979] and the novel approach to handing the "div **B** = 0" constraint has been developed by Powell [1994] and Powell et al. [1995, 1997].

The MAUS-MHD model for Io includes ion mass loading [Gombosi et al. 1996] and the approach of Tanaka [1995] for separating the magnetic field into a pure dipole plus perturbative parts [Gombosi et al. 1997] for cases where an intrinsic magnetic field for Io is included. The Tanaka decomposition is useful when the intrinsic field is strong and has large spatial gradients.

A graduate student, Konstantin Kabin, is working with the PI in the application of the MAUS-MHD code to study the flow of the Jupiter plasma torus ions past Io's extended neutral atmosphere and ionosphere. In particular, we have already improved the method of Gombosi et al. For computing the ion-neutral drag and charge-exchange terms so that they are expressed in

meeting [Combi et al. 1997] and by our graduate student Konstantin Kabin at the 1997 Spring terms of ion-density dependent quantities, instead of simply a scaled constant rate as is reasonable for the comet ionosphere interaction.

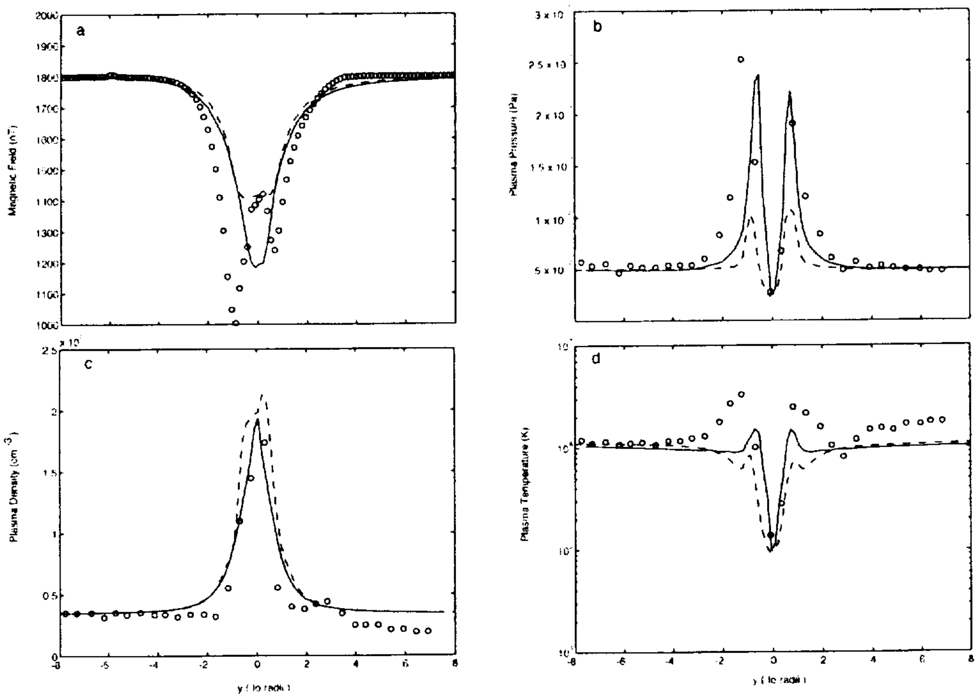


Figure 1. Comparison of MHD Mass-Loading Models with Galileo Particle and Field Measurements. The magnetic field measurements from Kivelson et al. (1996) are in (a), and the plasma density, pressure and temperature measurements from Frank et al. (1996) are in (b), (c), and (d), respectively. The solid model lines are for reflective boundary conditions and the dashed model lines are for fixed boundary conditions at an altitude of 150 km from Io by Combi et al. (1998b).

During the project year which is covered by this report, we made the first calculations using this model and applied them to reproduce and understand the measured plasma density, temperature, pressure, and magnetic field of Io observed during the December 7, 1995, flyby of the Galileo spacecraft within 900 km of Io [Kivelson et al. 1996; Frank et al. 1996; Gurnett et al. 1996]. Results have been presented by the PI at the April 1997 European Geophysical Society meeting [Combi et al. 1997] and by our graduate student Konstantin Kabin at the 1997 Spring AGU meeting [Kabin et al. 1997]. Copies of the abstracts are attached to the end of this report. Subsequently, a formal paper was written and submitted for publication in the Journal of Geophysical Research in May 1997 still during the project year which is the subject of this report. The paper was revised after the end of the project year in question for this report. Since the end of the project year (but before this writing) the paper been accepted and already appears in print Combi et al. [1998]. For this report we include in Figure 1 a summary plot comparing our model calculations directly with the Galileo data.

## PROGRAM THE NEXT YEAR

The work represents a multiyear effort which is continuing. With postdoc Dr. Rainer Bauske we will have completed the basic multi-species kinetic model for ion and neutral species for Io's and Europa's atmospheres based on Direct Simulation Monte Carlo methods developed in the computational fluid dynamics discipline. The model will share the same 3D adaptive grid as the MHD model and thus will serve as a fully-coupled set of to investigate the global structure of the satellite atmospheres, the interaction of the atmophere-ionosphere systems with the impinging Jupiter plasma torus ions, and the loss of neutrals and ions.

In the comet dust area we will complete our study of the dust coma of comet Austin (1990 V) with Dr. David Schleicher and Dr. David Osip, using our 3D time-dependent dust coma model with realistic light scattering properties and dust fragmentation.

We are also beginning a study of the production of cometary gaseous sodium from dust, as has been suggested by a number of investigators based on their analysis of various observations of comet Hale-Bopp.

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# EGS Abstract for Vienna, April, 1997

## INTERACTION OF IO'S ATMOSPHERE WITH JUPITER'S MAGNETOSPHERE: A 3D MULTISCALE MHD SIMULATION

**M.R. Combi**, T.I. Gombosi, D.L. DeZeeuw, K.G. Powell and K.S. Kabin (The University of Michigan, Ann Arbor, USA)

The results of our 3D multiscale MHD model describing the interaction of Jupiter's magnetosphere with Io's upper atmosphere and exosphere are presented. The effects of a conducting ionosphere, exospheric mass loading and a possible intrinsic magnetic field are taken into consideration. The equations of ideal magnetohydrodynamics are solved using a modern shock-capturing numerical technique. This method is applied on an adaptively refined unstructured grid. The combination of the adaptive refinement with the MUSCL-scheme allows detailed modeling of the near Io region, while still resolving both the upstream region and the satellite's wake.

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4. none
5. Oral presentation strongly preferred

Presented at the AGU Spring 1997 Meeting, Baltimore, Maryland

(Extracted from the AGU Meetings web page.)a

AN: SM52A-07

TI: A 3D MHD Simulation of Plasma Flow Around Io

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AB: The results of a 3D multiscale adaptive MHD simulation of the plasma flow around Io are presented and discussed. Effects of mass loading and ion-neutral momentum exchange are included in the model. Several possible scenarios are investigated, including the effects of conducting and non-conducting surface layers, various models of the neutral atmosphere, and the consequences of a potential intrinsic magnetic field. Comparison will also be given with Galileo's measurements.

SC: P

DE: 2732

DE: 2756

DE: 6218

MN: 1997 Spring Meeting